INTEREST OF FINITE ELEMENT ANALYSIS TO DETERMINE STRESS FIELDS AT THE SUMMIT OF A VY FLAP ABOUT ONE CLINICAL CASE

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1 INTRODUCTION

High closing tensions are an accepted cause of skin necrosis [1]. For linear scars, maximum tension is obtained along an axis perpendicular to the scar at the level of maximum excision but laterally, the tension decreases progressively [2] [3] [4]. In that case, the shape of skin necrosis is roughly parallel to skin margins (Figure 1).

After having performed a VY advancement flap, we observed an unusual shape of necrosis, like a broad-based key hole, with major axis perpendicular to skin margins at the summit of the flap where a corner stitch has been performed (Figure 2). Major perpendicular axis and keyhole shape of the necrosis are both unusual. As there was a lot of tension when suturing, we discuss the possibility to explain this shape by determining the stress field with mathematical modeling.

Based on a VY flap simulation during an abdominoplasty (Figure 3), we developed a mathematical model based on the finite element analysis (FEA), in order to determine the stress field by simulating the mechanical behavior of human skin during the suture.

The work is divided in two parts. The first part of the modeling determines the orthogonal initial stress fields representing the in vivo skin tension by inverse method. The second part determines stress fields when suturing the corner stitch. Results are expressed in numerical and graphic form and compared to clinical case.

2 CLINICAL CASE

A 83 year old patient presents a dedifferentiated latéro-thoracic liposarcoma without metastasis. The major axis measures 10 cm. A wide resection is performed including major pedicle of latissimus dorsi muscle. To cover the defect, a VY advancement flap is done, with two lateral expansions according to Pacman flap [5] (Figure 4). The flap is based on latissimus dorsi minor pedicles and advancement is permitted by medial muscle incision (Figure 5). The value of summit angle's flap is about 50°.

The postoperative period is marked by skin necrosis and skin epidermolysis on either side of the summit. Both have a broad-based keyhole shape with major axis perpendicular to skin margins (Figure 2). Healing occurred by secondary intention.

3 MATERIAL AND METHOD

3.1 MATERIAL

Natural tension of the skin is due to prestress. To determine the orthogonal prestress fields σ_x and σ_y, a rectangular defect is performed in vivo during an abdominoplasty in a 38 years old woman in accordance with the patient and the ethical committee approval of the university hospital. A rectangular mesh was drawn before skin incision. The dimension of one mesh's square is 14x14 mm and the dimension of the rectangle is 42x84mm. The length of the rectangular defect d_2 is parallel to the vertical plane represented by y direction, the width d_1 parallel to the horizontal plane represented by x direction (Figure 3a). Horizontal and vertical skin deformations after incision are due respectively to horizontal prestress field σ_x and to vertical prestress field σ_y (Figure 3b). Width of the rectangle is approximately aligned with Langer's lines [6], lines which define the direction within the skin (along which the skin) has the least flexibility.

For the modeling, a planar non-linear bi-dimensional FEM was used. The numerical simulation has been carried out with Ansys® v12 software. This model was based on Arruda and Boyce's eight-chain model and Bischoff and al.'s finite element model of skin [7] [8].

3.2 METHOD

FEA starts with creating the geometry of the rectangular defect according to Figure 3a. Dimensions of the modeled defect are identical to clinical case. It is discretized into triangular finite elements. The stress fields at the boundary of the sought region are identified by the inverse method using a finite element calculation by comparing modeling with the deformed rectangular hole obtained experimentally (Figure 3b).

Second step, the FEA created the geometry of the VY flap just before the corner stitch (Figure 7). The model is based on geometry of VY flap performed during the abdominoplasty (Figure 3d). The value of apex angle’s flap is also about 50°. The orthogonal prestress fields calculated above have been integrated as an additional parameter in the model. Then, material properties boundary conditions and forces are applied to the model and results are expressed in numerical and graphic form.

To solve the bi-dimensional finite element problem, the following assumptions were made at the first step:

- The plane stress hypothesis was supposed for all elements.
- The thickness of the human skin was set to be 1 mm.
- The wound is considered to be small compared to the size of the skin sheet (560 x 406 mm).
- Prescribed zero displacement is set to left (x direction) and bottom (y direction) edge’s nodes (Figure 6).
- Mesh is denser around the object of interest.

At the second step, new assumptions are added to simplify the modelling (Figure 7):

- The horizontal symmetry of the model allows modeling half of the flap,
- The summit of the flap is retracted because of the horizontal prestress field $\sigma_{x,}$
- But skin margins are not loaded by the orthogonal prestress,
- The apex of the flap is immovable when corner stitch is performed,
- Points used for the corner stitch are the closest to the apex N (corresponding to point M of the Figure 7).

4 RESULTS

In Figure 3a, initial dimensions of the rectangle are d1=42mm and d2=82mm. After incision, the orthogonal prestress fields deform the rectangle and dimensions of the rectangular defect become d1’=84mm and d2’=76mm. From inverse FEA using the nonlinear material model, the prestress is found to be σ_x=6.4kPa σ_y=0.3kPa (Figure 8).

After integrating these values in the numerical model, biaxial loading determine the maximum stress in the corner stitch. Values of maximum stress are σx=45.3kPa σy=93.4kPa. The results are expressed in graphic form with the representation of iso-stress lines at the summit of the flap (Figure 9). The shape of the vertical iso-stress line σ_y for a stress equal to 18.8kPa (border of the sky blue surface) is similar to a broad-based keyhole, with a major axis perpendicular to the skin margin. This shape is comparable to the necrosis observed in our clinical case.

5 DISCUSSION

5.1 FINITE ELEMENT ANALYSIS OF SKIN

FEA is a powerful computer-based tool widely used by engineers and scientists for understanding the mechanics of physical or biological system like the skin [9] [10].

FEA seeks to approximate the behavior of an arbitrarily shaped structure under general loading and constraint conditions with an assembly of discrete regions or domains called '*elements*'. These elements have regular geometric shapes with known solutions and are connected at the edges called '*nodes*'. The behavior of the structure is obtained by analyzing the collective behavior of the elements. Elements are the building blocks of a finite element model, they are used to divide a given complex physical domain into simple mathematical representation (simple shapes) with known solutions.

FEA of the skin has many applications like virtual surgery [11] [12], cutaneous flaps [13] [14] and aging of the skin [15]. It has ever been used to describe stress fields after simple sutures [3] or after flaps [9].

Concerning our modeling, two points should be discussed. First point, mechanical skin properties of the patient with necrosis and the patient used to determine prestress fields are widely different. The modeling uses data from a 38 years old woman with an abdominal skin excess while necrosis appeared at the back of an 83 year old man [16] [17]. Nevertheless, as the aim of the study is to determine the graphic representation of the stress fields when suturing the corner stitch, it is not in itself a problem. It would have been a problem if we wanted to identify the values of stress responsible for the necrosis. Second point, values of prestress were obtained by inverse method. Values extracted from literature [16] or experimental methods on the patient like indentation, suction, torsion tests, wave propagation and extensometer could have been also used [18]. Nevertheless, the values of prestress calculated in our study are comparable to literature data. A value of σ_x superior to σ_y corresponds to anisotropic properties of the skin [19] [20].

The particular shape of the necrosis is related to the particularities of the suture at the summit of the VY flap. It is at this level that the tension is maximal because the distance to suture is the longest (reference to other article joint with this one). Moreover, on either side of the summit, there is an angulation equal to 25° in our study.

5.2 SKIN TENSION AND NECROSIS

High closing tensions are an accepted cause of wound slough [1]. The relationship of tension, blood flow, and flap viability is well established [21] [22] [23]. Barnhill demonstrates that tension has important effects on the superficial dermal microvasculature, resulting in impedance and obliteration of blood flow. An average force of 11.9 N, accompanied by a mean strain of 10.3%, resulted in occlusion of all vessels [22].

Two solutions to the problem of closing skin defects under tension are common: undermining [24] [25] and stretching the skin [26] [2]. Undermining has inherent drawbacks, because of the damage to the feeding vessels ~~of the skin so undermined~~ like skin-edge necrosis and seroma. Undermining results in decreases in skin blood flow and skin oxygenation [25] [27]. It is necessary to find the right balance between reduced blood flow and decreased tension [28]. Skin stretching reduces wound closing tension [2] [29]. For Melis, the additional advantage of skin stretching over that of undermining alone is clearly shown [2] [27]. Cyclic skin stretching seems even more efficient [30] [31].

In our clinical case, both undermining and excessive tension probably contributes to the necrosis:

- In case of VY advancement flap, the tension of the suture is maximal at the summit of the flap,
- In human, the highest skin stress is found in the back [16],
- Skin is undermined from latissimus dorsi muscle, involving cutting musculocutaneous perforating vessels (Figure 5).

Nevertheless, similarities between the shape of necrosis and the calculated stress field discuss the major role of skin tension.

In this clinical case, in order to reduce closing tension, we could have propose:

- A reduction of the value of the angle at the summit of the flap. Nevertheless, the longer is the flap the less it is vascularized because summit is free of vascular support (Figure 5),

- A keystone flap would have been more appropriate because distance to suture around it is smaller and more homogeneous compared to the advancement of a lonely V-Y flap (reference to other article joint with this one). Moreover, all skin paddle would have been supported by muscle.

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6 CONCLUSION

In a precedent study, we proposed a very simple modeling of VY flap with simple mathematical equations. Even if informations are limited, this model explains the relation between the distance to suture according to flap's shape and flap advancement and the particularity of the corner stitch at its summit.

To evaluate stress fields, we developed a mathematical model to describe stress fields using FEA. The results of modeling correlate well with the clinical case. Our method is an original approach for describing the particular shape of a necrosis.

7 CONFLICT OF INTEREST

There is no conflict of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

8 ACKNOWLEDGMENT

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10 ICONOGRAPHIE

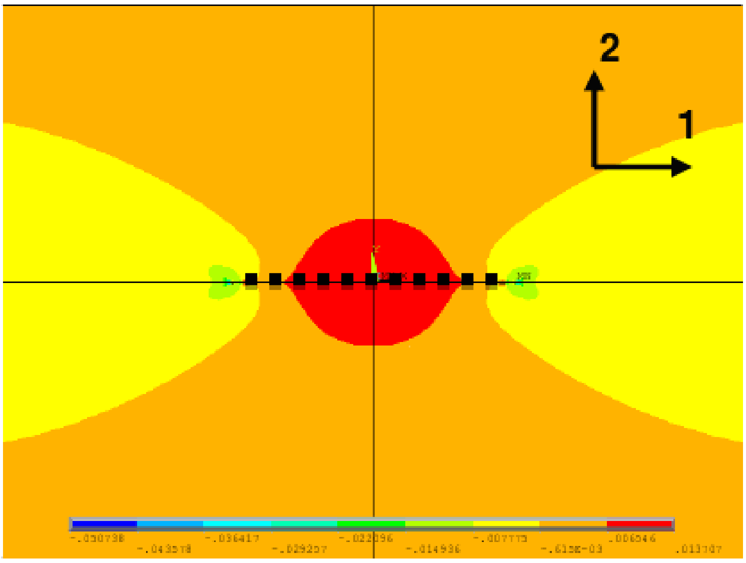

Figure 1. Stress fields when suturing skin incision (dotted line) in an orthotropic model. With permission from [4]. Values of stress are expressed in Pascal.

Figure 2. Skin necrosis and epidermolysis with a shape of broad-based key hole at the summit of the flap

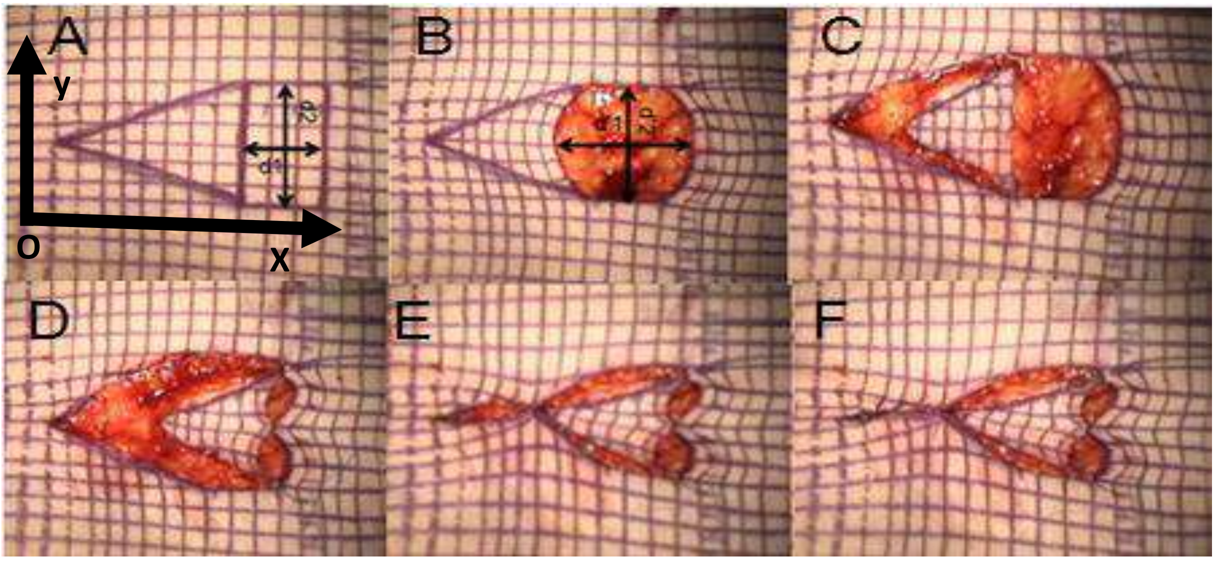

Figure 3. A rectangular defect and a VY advancement flap are performed during an abdominoplasty to characterize skin properties.

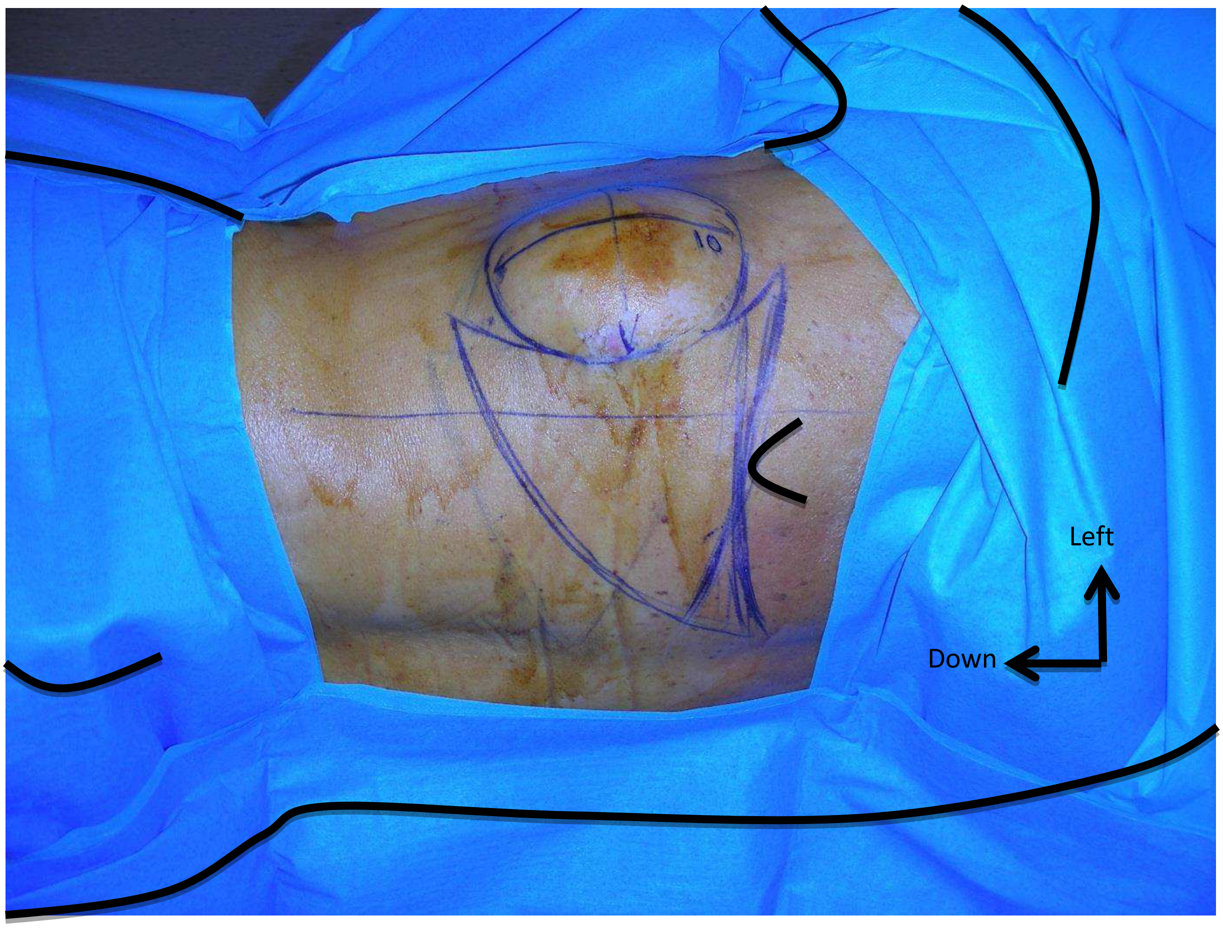

Figure 4. Latero-thoracic liposarcoma. VY flap design. (Patient positioned in right lateral decubitus position).

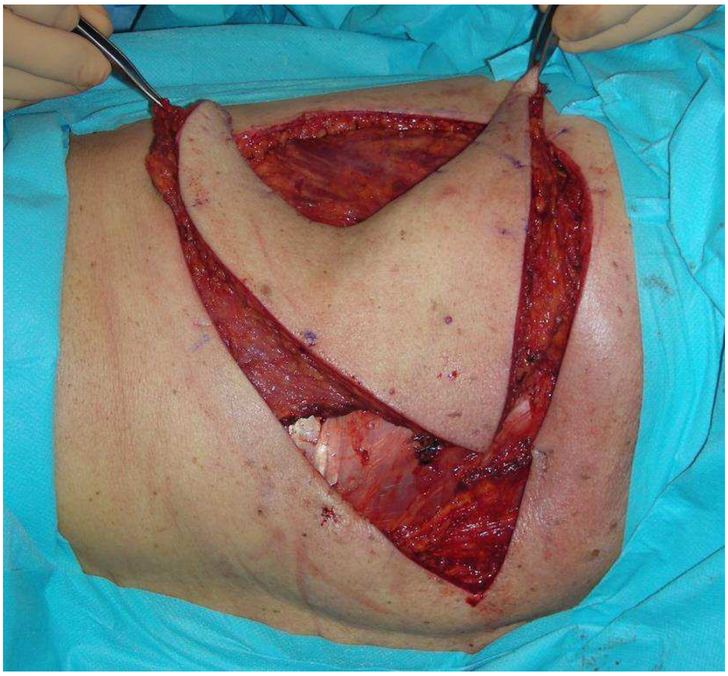

Figure 5. VY advancement flap with medial latissimus dorsi incision, summit's flap and medial skin without muscular vascular support.

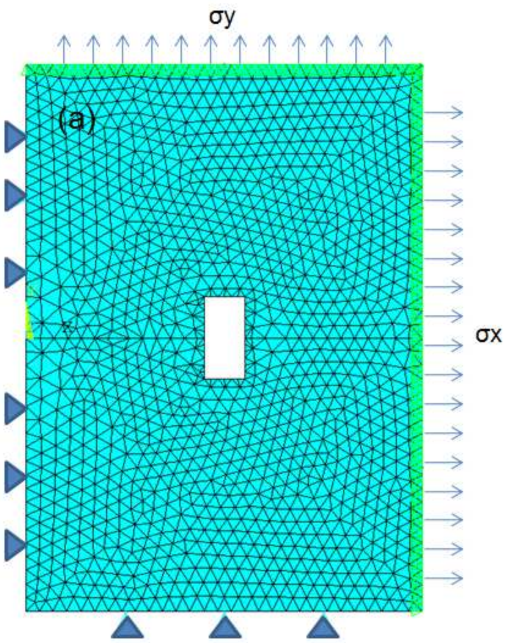

Figure 6. Geometric model, meshing and boundary conditions of the domain with rectangular hole.

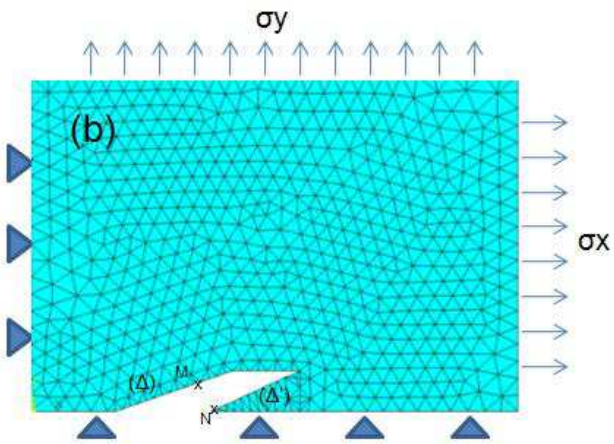

Figure 7. . Geometric model, meshing and boundary conditions of the V-Y flap.

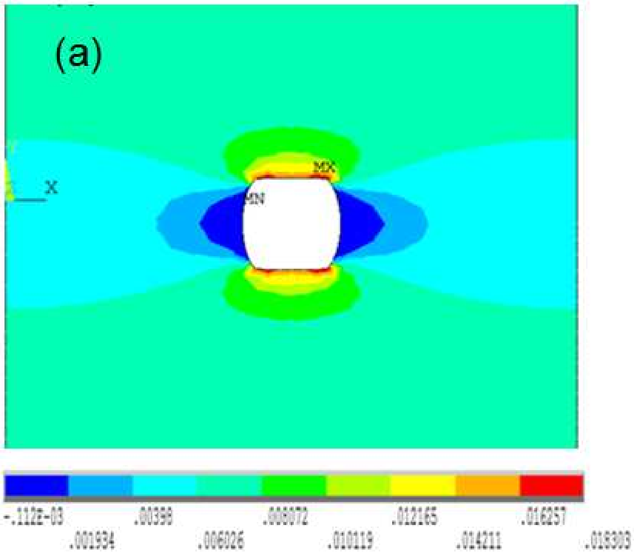

Figure 8. stress field σ_x calculated by inverse method. Values of stress are expressed in Pascal.

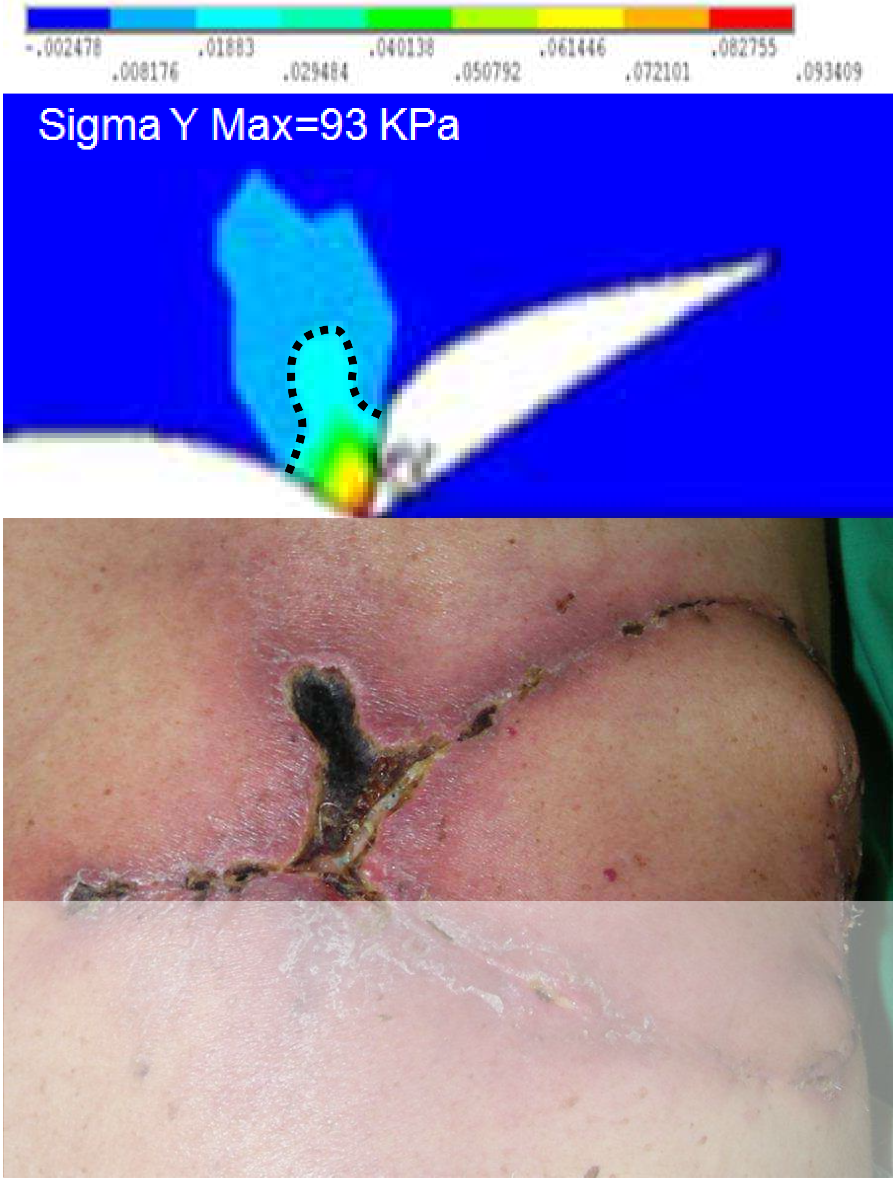

Figure 9. The shape of the vertical iso-stress line σ_y for a stress equal to 18.8kPa (dotted line) is similar to the clinical case necrosis. Values of stress are expressed in Pascal.